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Late Cretaceous through Cenozoic Strike-Slip Tectonics of Southwestern Alaska

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ABSTRACT

New geologic mapping and geochronology show that margin-parallel strike-slip faults on the western limb of the southern Alaska orocline have experienced multiple episodes of dextral motion since ~100 Ma. These faults are on the upper plate of a subduction zone ~350–450 km inboard of the paleotrench. In southwestern Alaska, dextral displacement is 134 km on the Denali fault, at least 88–94 km on the Iditarod–Nixon Fork fault, and perhaps tens of kilometers on the Dishna River fault. The strike-slip regime coincided with Late Cretaceous sedimentation and then folding in the Kuskokwim basin, and with episodes of magmatism and mineralization at ~70, ~60, and ~30 Ma. No single driving mechanism can explain all of the ~95 million-year history of strike-slip faulting. Since ~40 Ma, the observed dextral sense of strike slip has run contrary to the sense of subduction obliquity. This may be explained by northward motion of the Pacific Plate driving continental margin slivers into and/or around the oroclinal bend. From 44 to 66 Ma, oroclinal rotation, perhaps involving large-scale flexural slip, may have been accompanied by westward escape of crustal blocks along strike-slip faults. However, reconstructions of this period involve unproven assumptions about the identity of the subducting plate, the position of subducting ridges, and the exact timing of oroclinal bending, thus obscuring the driving mechanisms of strike slip. Prior to 66 Ma, oblique subduction is the most plausible driving mechanism for dextral strike slip. Cumulative displacement on all faults of the western limb of the orocline is at least 400 km, about half that on the eastern limb; this discrepancy might be explained by a combination of thrusting and unrecognized strike-slip faulting.

Introduction

Major strike-slip fault zones have long been recognized in western interior Alaska (Grantz 1966; figs. 1, 2). The Denali and Iditarod–Nixon Fork faults, in particular, are linear, through-going structures that have well-defined topographic expressions and are comparable in scale to the San Andreas and Alpine fault systems. They occur in the continental back-arc region of the present-day Aleutian subduction zone and strike roughly parallel to the curved continental margin. A number of studies have addressed the sense, timing, and amount of motion on the major margin-parallel strike-slip faults on the eastern limb of the southern Alaska orocline (e.g., Eisbacher 1976; Gabrielse 1985; Dover 1994; Lowey 1998) and in the hinge area of the orocline (Cole et al. 1999). Strike-slip faulting on the western limb has not been as thoroughly documented in the literature, and an up-to-date synthesis has been lacking. Approximately 88–94 km of dextral offset was documented for the Iditarod–Nixon Fork fault (Miller and Bundtzen 1988), and 145–153 km of dextral offset (revised herein to ~134 km) has been suggested for the Denali fault (Blodgett and Clough 1985). However, Csejtey et al. (1996) argued that Cenozoic dextral displacement across the Denali fault in the area of the Cantwell Basin (fig. 1) cannot exceed a few tens of kilometers, and Redfield and Fitzgerald (1993) suggested that, at least since the Miocene, the sense of motion in this area has been sinistral, not dex-

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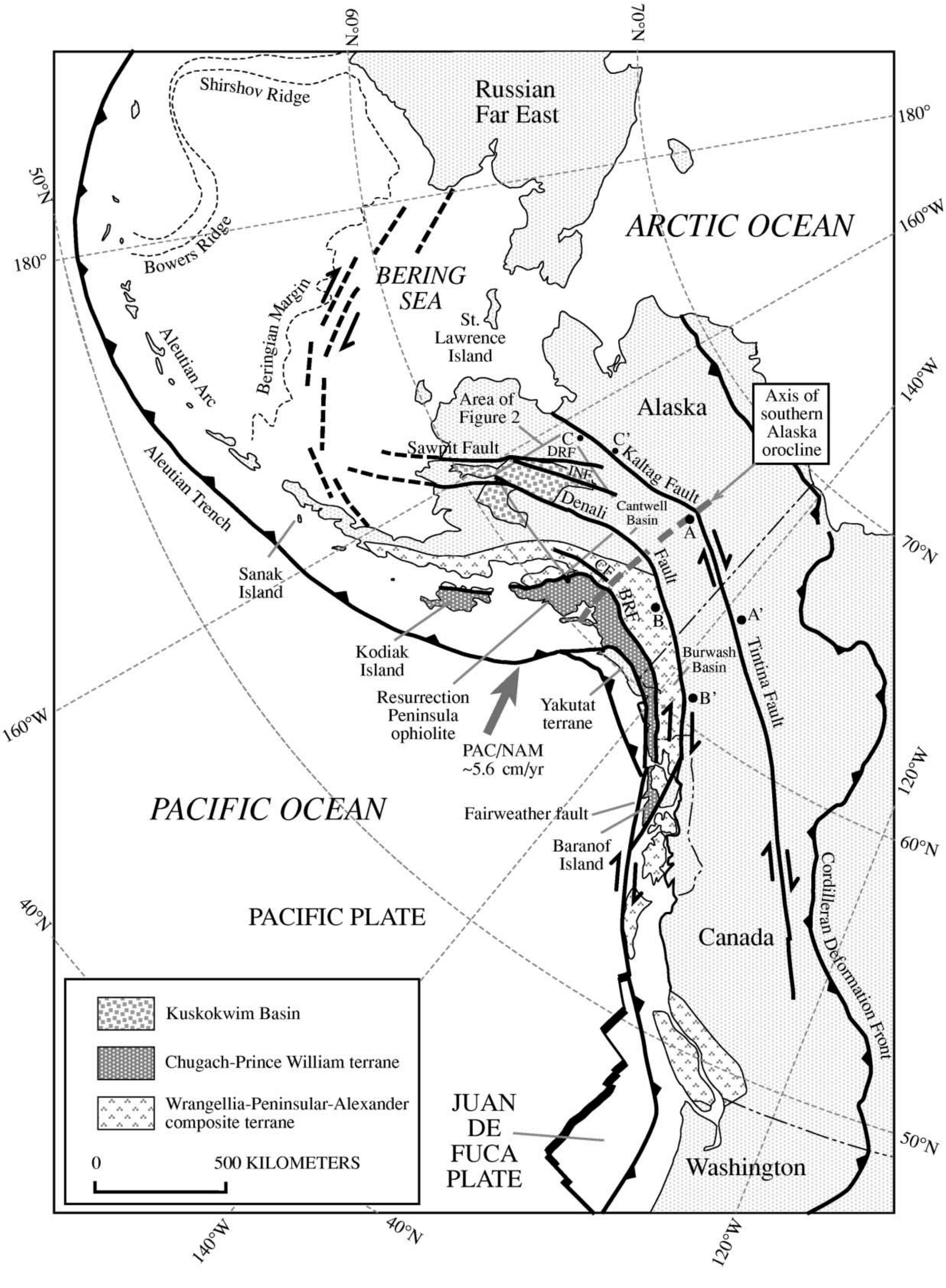

Figure 1. Map of Alaska, the northeastern Pacific, and parts of Canada and the Russian Far East showing key features mentioned in text. Geologic offsets *A* and *A′* (Tintina fault), *B* and *B′* (Denali fault), and *C* and *C′* (Kaltag fault) are indicated. *BRF*, Border Ranges fault; *CF*, Castle Mountain fault. Strike-slip faults of Beringian margin after Worrall (1991).

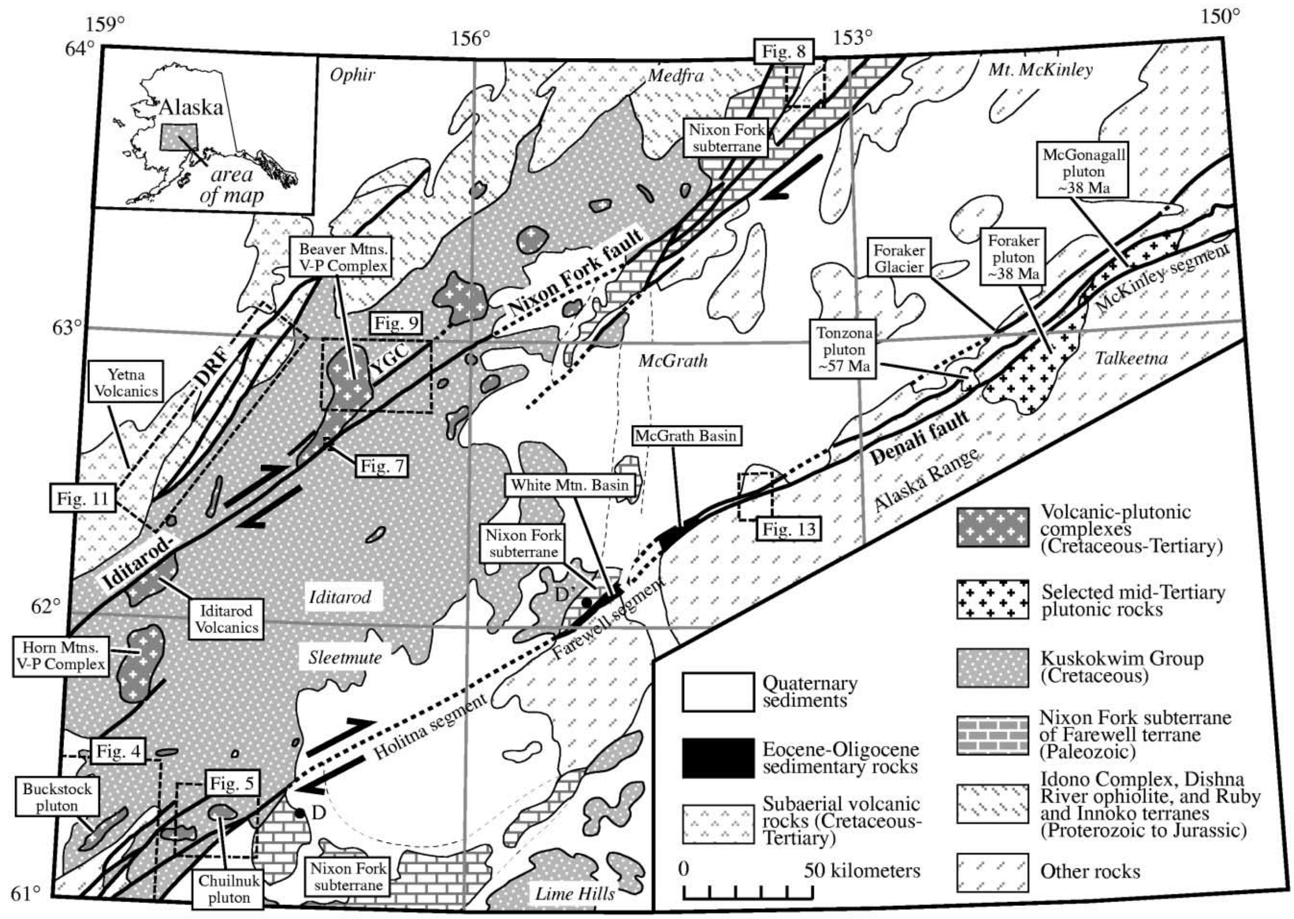

Figure 2. Generalized geologic map of part of southwestern Alaska emphasizing strike-slip faults and key features that bear on their interpretation. *YGC*, Yankee-Ganes Creek fault; *DRF*, Dishna River fault. Area of the Kuskokwim basin is delineated by the Kuskokwim Group. *D* and *D'* mark offset Silurian reefs (R. Blodgett, written communication, 1999).

tral. In light of these controversies, the main purpose of this article is to document the sense, timing, and amount of motion on these margin-parallel strike-slip faults—potentially valuable geologic constraints that might be brought to bear on plate reconstructions in the Pacific and on the history of terrane transport. The history of strike-slip faulting is also important for economic geology reasons: a number of gold and mercury deposits are spatially associated with the major strike-slip faults (fig. 3), one major gold trend is offset 90 km across the Iditarod–Nixon Fork fault, and, as we suggest here, mineralization during three time intervals (~70, ~60, and ~30 Ma) was coeval with strike-slip movements.

Our conclusions are regional in scope, but the data we describe in detail are based primarily on new mapping in the Iditarod, McGrath, and Sleetmute 1 : 250,000-scale quadrangles (fig. 2), performed by the U.S. Geological Survey and the Alaska Division of Geological and Geophysical Surveys (see, e.g., Miller and Bundtzen 1994; Decker et al. 1995; Bundtzen et al. 1997, 1999; and U.S. Geological Survey unpublished mapping).

Regional Geology

This article focuses on the Kuskokwim Mountains region of southwestern interior Alaska, a largely unglaciated area, characterized by rolling hills as high as 900 m that separate wide, sediment-filled valleys. Bedrock is poorly exposed due to extensive vegetation, local loess cover, and the antiquity of the landscape. The dominant bedrock unit is the Upper Cretaceous Kuskokwim Group (Cady et al. 1955) that is largely composed of turbiditic sand-

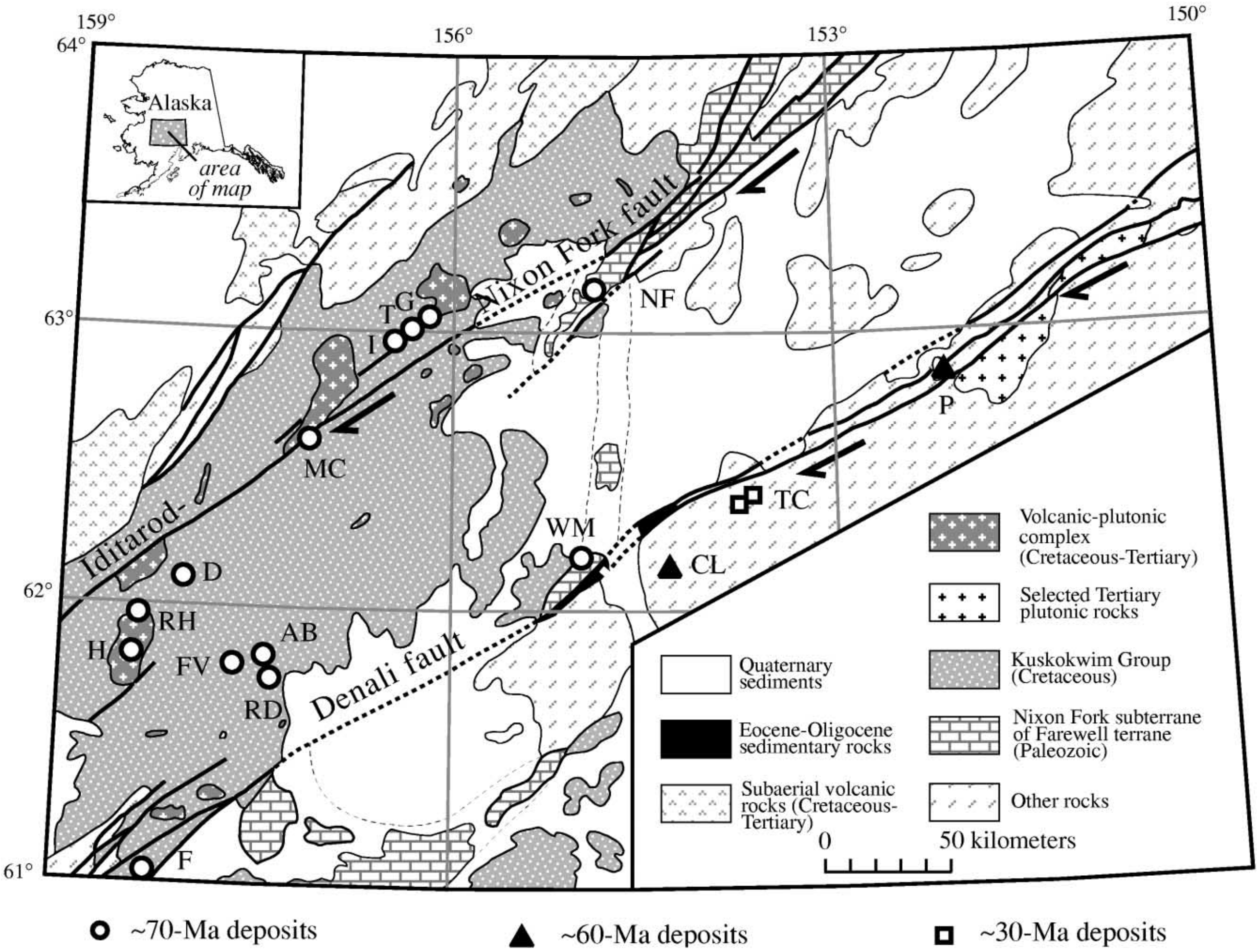

Figure 3. Same area as figure 2 showing key mineral deposits that have some bearing on the Late Cretaceous to Tertiary tectonic history. Symbols correspond to ages as shown. Abbreviations for deposits are as follows: *AB*, Alice and Bessie; *CL*, Chip Loy; *D*, Donlin Creek; *F*, Fortyseven Creek; *FV*, Fairview; *G*, Goss Gulch; *H*, Horn Mountains; *I*, Independence; *MC*, Moore Creek; *NF*, Nixon Fork; *P*, Purkeypile; *RD*, Red Devil; *RH*, Rhyolite; *T*, Telephone Hill; *WM*, White Mountain.

stone and shale (fig. 2). This basin-fill sequence overlies a number of older basement terranes of varied origin that were amalgamated by mid-Cretaceous time (Decker et al. 1994; Patton et al. 1994). The waning stages of Kuskokwim Group deposition were accompanied by regional volcanism and intrusion (Miller and Bundtzen 1994). A number of volcanic-plutonic complexes of Late Cretaceous and early Tertiary age partly intrude and partly overlie the Kuskokwim Group; approximately coeval felsic and intermediate dikes also cut the sedimentary rocks. In the eastern part of figure 2, two younger units bear on the displacement history of the Denali fault: mid-Tertiary plutons of the Alaska Range and Eocene to Oligocene nonmarine sedimentary rocks of the McGrath and White Mountain basins.

Pre-Mid-Cretaceous Rocks. Older bedrock of the Kuskokwim region includes Proterozoic to Lower Cretaceous units of various types. West of the Kuskokwim basin, the oldest rocks are assigned to the Early Proterozoic Idono Complex (Miller et al. 1991) and the Late(?) Proterozoic to Paleozoic Ruby terrane (Jones et al. 1987; Patton et al. 1994). The fault-bounded Idono Complex consists of amphibolite-grade granitic to dioritic orthogneiss, amphibolite, and metasedimentary rocks. Rocks of the Ruby terrane in the area of interest are also fault bounded and consist of greenschist facies meta-igneous and metasedimentary rocks (Chapman et al. 1985; Miller and Bundtzen 1994). Paleozoic-Mesozoic oceanic crust and subduction zone assemblages also crop out on the west side of the Kuskokwim basin (fig. 2). These include slivers of dismembered Jurassic ophiolite (Dishna River mafic-ultramafic rocks of Miller [1990]) and volcanic and sedimentary rocks of the Mississippian to Triassic Innoko terrane (of Jones et al. [1987]).

Basement rocks on the east side of the Kuskokwim basin consist of parts of the Nixon Fork, Dillinger, and Mystic subterranes. Depositional relationships between the three suggest that they are facies of a single terrane, referred to as the "Farewell terrane" by Decker et al. (1994). The Nixon Fork subterrane, which is a platformal carbonate succession of Late Proterozoic to Devonian age, provides the best evidence for offset across the Denali fault in the study area; accordingly, the Nixon Fork subterrane is indicated in figure 2 by a special pattern, whereas the rest of the Farewell terrane is included with "other rocks."

Kuskokwim Basin Fill. Upper Cretaceous sedimentary and minor volcanic rocks of the Kuskokwim Group depositionally overlie structural slivers of the pre-Cretaceous bedrock units (fig. 2). The Kuskokwim Group was deposited primarily by turbidity currents into an elongate, probably strike-slip basin beginning in Late Cretaceous time (Miller and Bundtzen 1992, 1994). Cady et al. (1955) estimated a minimum thickness of 7.5 km. The basinal sequence is successively overlapped by shoreline facies, suggesting that shallow-water strata were deposited when the sedimentation rate exceeded the subsidence rate. Fossils from the Kuskokwim Group are mainly Turonian but range in age from Cenomanian to Campanian or Maastrichtian. The youngest fossils are poorly diagnostic spores. Better control is provided by tuff, interbedded with shoreline facies rocks near the top of the Kuskokwim Group, that has yielded a 77-Ma K/Ar age on biotite (Miller and Bundtzen 1994). For the purposes of this article, we will take this as the approximate upper age limit of the Kuskokwim Group, which accordingly would have an age range from about 95 to 77 Ma.

Late Cretaceous and Tertiary Igneous Rocks. In the Kuskokwim region, Late Cretaceous and Tertiary igneous rocks are of four main types: (1) volcanic-plutonic complexes; (2) subaerial volcanic fields; (3) felsic to intermediate dikes, sills, and stocks; and (4) volumetrically minor altered intermediate to mafic dikes (Miller and Bundtzen 1994; Bundtzen and Miller 1997). Only the first two types are of sufficient aerial extent to show on figure 2. The volcanic-plutonic complexes are important to the strike-slip history because they provide evidence for timing and amount of movement.

Calc-alkaline volcanic-plutonic complexes of Late Cretaceous and early Tertiary age intrude and locally overlie strata of the Kuskokwim Group (Bundtzen et al. 1988; Miller and Bundtzen 1994). About 20 of these complexes, which range from as small as 8 km^2 to as large as 650 km^2, crop out in a broad, 450-km-long, northeast-trending belt (Miller et al. 1989; Moll-Stalcup 1994; Bundtzen and Miller 1997). The majority of the volcanic-plutonic complexes lie in the focus area of this report (fig. 2); three additional complexes are located to the southwest. These complexes generally consist of intermediate to mafic, and locally rhyolitic, tuffs and flows and comagmatic monzonite to quartz monzonite composite plutons. Hornfels aureoles, as wide as 2 km, surround most of the larger plutons and developed in both the clastic sedimentary and overlying volcanic rocks. Conventional K/Ar and a limited number of ^{40}Ar/^{39}Ar ages of volcanic rocks range from about 76 to 63 Ma (Moll et al. 1981; Miller and Bundtzen 1994; Decker et al. 1995; Bundtzen et al. 1999). The comagmatic plutons yield ages ranging from about 71 to 67 Ma, although some younger ages (to 60 Ma) have been reported (Moll et al. 1981; Miller and Bundtzen 1994; Decker et al. 1995; Bundtzen et al. 1999). There is no significant time break between deposition of the uppermost Kuskokwim Group (Campanian) and initial volcanism associated with the volcanic-plutonic complexes. Indeed, the volcanic rocks are locally conformable and disconformable with the Kuskokwim Group (Miller and Bundtzen 1994).

Volcanic rocks of similar Late Cretaceous and early Tertiary age, but which do not have associated comagmatic plutons, form locally extensive fields in the Kuskokwim region. These volcanic sequences are largely andesitic in composition but commonly have dacite, rhyolite, and minor basalt. Subaerial volcanic flows, tuffs, and locally domes compose the fields, which individually cover areas as large as 5000 km^2. Conventional K/Ar ages range from about 71 to 54 Ma, and, like the volcanic-plutonic complexes, major- and trace-element geochemistry indicates broad calc-alkaline trends.

Hypabyssal felsic to intermediate dikes, sills, and stocks of Late Cretaceous and early Tertiary age crop out discontinuously across the Kuskokwim region. Although of similar age, they are probably not directly related to the volcanic-plutonic complexes. The hypabyssal rocks are characterized by a distinctly peraluminous chemistry and commonly contain garnet phenocrysts, suggesting they represent melted continental crust (Miller and

Bundtzen 1994). These porphyritic intrusive rocks are spatially related to gold-bearing veins and to placer gold occurrences, making them an important exploration target. K/Ar ages for the hypabyssal rocks appear to be bimodal, centering around 70 and 65 Ma (Miller and Bundtzen 1994).

Intermediate to mafic dikes comprise a volumetrically minor, fourth type of Late Cretaceous and early Tertiary igneous rock of the Kuskokwim region. The dikes are generally less than 3 m wide and are ubiquitously altered to an assemblage of chlorite, calcite, and silica, a fact that has led to their moniker, "silica-carbonate dikes" (Cady et al. 1955). These dikes are generally not related to any obvious parent bodies. A number of mercury prospects are spatially associated with the dikes; this association is not considered genetic but rather structural in nature in that both the dikes and mineralized fluids followed the same structural conduits, and (or) the dikes provided a favorable structural competency contrast for dilation.

Major Strike-Slip Faults and Their Displacement Histories

The three most significant fault systems in the area of this study—the Denali, Iditarod–Nixon Fork, and Dishna River systems—are discussed below. Between these major faults lie a number of lesser faults that roughly parallel the main structures. These are not discussed in detail, but are shown on regional quadrangle maps (e.g., Patton et al. 1980; Miller et al. 1989; Miller and Bundtzen 1994).

Denali Fault. The Denali fault system is one of the most important strike-slip faults in the North American Cordillera (fig. 1). It is composed of numerous subsidiary strands along its approximately 2000-km length in Alaska and Canada. In eastern Alaska and Yukon, Eisbacher (1976) estimated at least 300 km of dextral offset based on a correlation between the Nutzotin Mountains flysch sequence in Alaska and the Dezadeash flysch sequence in Yukon. Lowey (1998) refined this estimate by suggesting a matchup between distinctive boulder conglomerate units in these two areas, indicating 370 km since mid-Cretaceous time (fig. 1, *B* and *B′*).

In the area of our study (fig. 2), the Denali fault has somewhat less displacement. Along the Farewell segment (fig. 2), it cuts and offsets both the Kuskokwim Group and the Farewell terrane. A Late Silurian to Early Devonian algal reef within the Nixon Fork subterrane (of the Farewell terrane) provides the best measure of displacement in this area. Blodgett and Clough (1985) originally proposed that the reefs are offset by 145–153 km, but map relations suggest that 134 km is a better estimate. This new estimate was obtained by projecting along strike from the two reef tracts to the fault and measuring the offset (*D–D′* in fig. 2). Even without this distinctive reef facies, the map offset between the Kuskokwim and Farewell contact is approximately the same. Displacement must postdate deposition of the Cenomanian to Campanian Kuskokwim Group strata, which are cut by the fault. Following is a discussion of specific evidence for fault movement progressing from youngest to oldest.

Quaternary offsets have so far been recognized only in the eastern part of figure 2. Large glaciers flowing north from the Alaska Range (e.g., Foraker Glacier, fig. 2) have been deflected 5–7 km in a dextral sense (Grantz 1966). These glaciers could not have existed before the rise of the modern Alaska Range, an event dated at 5.6 Ma by apatite fission track (Redfield and Fitzgerald 1993). Redfield and Fitzgerald explained the observed dextral offsets as the consequence of clockwise block rotations between unspecified strands in a sinistral fault system. We disagree with this interpretation because it can only work if the blocks somehow rotate faster than the master faults are displacing them.

The White Mountain and McGrath basins (fig. 2) are exposed between strands of the Denali fault along the north flank of the western Alaska Range. These basins correspond to part of a much broader lowland area referred to as the "Minchumina basin" by Kirschner (1994). They are filled with Tertiary nonmarine sandstone, conglomerate, and minor coal (Dickey 1984; Bundtzen et al. 1997; Ridgway et al. 2000). The location of the basins within the fault system and the fact that basinal sediments lie at lower elevations than the surrounding basement rocks that provided the sediment source together suggest syntectonic deposition. Spores suggest a late Oligocene to possibly earliest Miocene age for the White Mountain basin (Ridgway et al. 2000). McGrath basin strata have yielded pollen of Eocene to Oligocene age but are intruded by a 45.5-Ma dike, which restricts the age to Early or Middle Eocene (Bundtzen et al. 1997). Neither the sense nor amount of fault displacement along this portion of the Denali fault system is known during this interval.

Along the McKinley segment in the central Alaska Range (fig. 2), truncated plutons on opposite sides of the fault provide good evidence for dextral movement of about 38 km since their 38-Ma emplacement (Reed and Lanphere 1974). The Foraker pluton, south of the fault, and the McGonagall pluton, north of the fault, are strikingly similar in

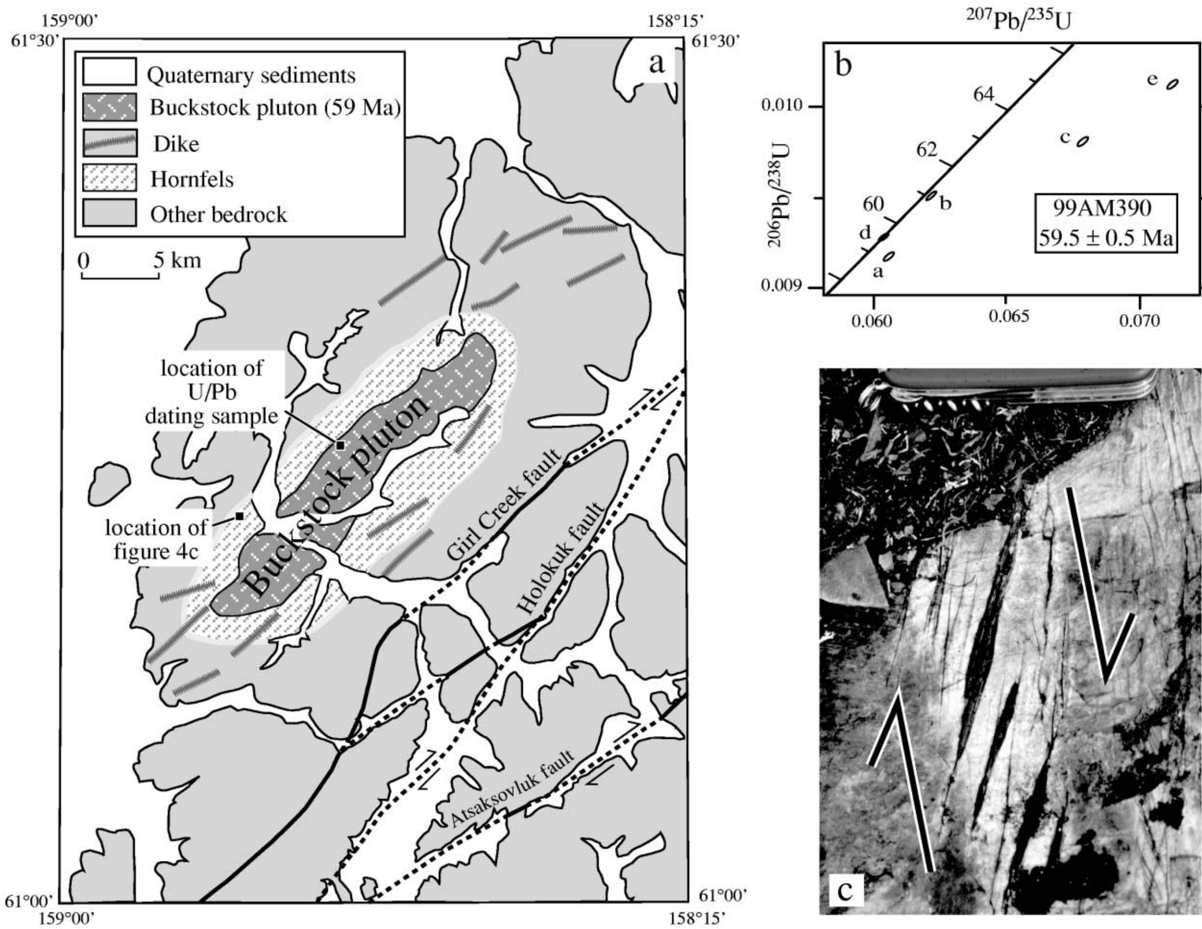

Figure 4. *a*, Geologic map of the Buckstock pluton and surrounding areas. *b*, U/Pb concordia diagram. *c*, Outcrop photograph of contact-metamorphosed Kuskokwim Group in the aureole of the Buckstock pluton, showing pervasive tourmaline- and chlorite-filled fractures, which formed during pluton emplacement in a northeast-striking subvertical zone of dextral shear.

megascopic appearance, mineralogy (both are hornblende-biotite granodiorite), geochemistry, and K/Ar age. Moreover, the matchup across the fault is unique, as there are no other plutons of the same age that have been thusly truncated.

In the same region, the Tonzona pluton provides evidence for an earlier episode of motion along a more northerly strand of the Denali fault system. This pluton consists of biotite-muscovite granite (Reed and Nelson 1980); a biotite separate yielded a K/Ar age of 57.4 Ma (Lanphere and Reed 1985), that is, latest Paleocene. Reed and Nelson's (1980) mapping implies to us that the pluton intruded across the linear trace of a high-angle fault, thus sealing this older splay of the Denali fault system. Nonmarine sandstone, conglomerate, and minor tuff are preserved in a down-dropped block along this fault. Plant fossils of probable Paleocene age (Reed and Nelson 1980) indicate that these sedimentary rocks cannot be significantly older than the Tonzona pluton; the tight time constraints are best met if sedimentation and faulting were synchronous.

Evidence for a dextral sense of motion during this same time comes from a newly discovered pluton in the western part of the Sleetmute quadrangle, 350 km to the southwest (fig. 2). The Buckstock pluton, composed of biotite-hornblende granodiorite, is an elongate, 5 × 24-km body, the long axis of which trends northeast, parallel to the regional strike-slip faults (fig. 4*a*). A zircon separate yielded a concordant U/Pb age of 59.5 ± 0.5 Ma (fig. 4*b*; table 1). In the contact aureole northwest of the pluton, abundant northeast-striking subvertical en-echelon tension gashes cut hornfels and indicate a dextral shear component (fig. 4*c*). The fractures are

Table 1. U/Pb Data and Isotopic Ages for Buckstock Pluton (Sample 99AM390A)

Fraction/size (μm)[a]	Wt (mg)	Concentration U	Concentration Pb^*	Isotopic composition[b] $^{206}Pb/^{204}Pb$	Isotopic composition[b] $^{206}Pb/^{207}Pb$	Isotopic composition[b] $^{206}Pb/^{208}Pb$	Apparent ages (Ma)[c] $^{206}Pb^*/^{238}U$	Apparent ages (Ma)[c] $^{207}Pb^*/^{235}U$	Apparent ages (Ma)[c] $^{207}Pb^*/^{206}Pb^*$	Th-corrected ages (Ma)[d] $^{206}Pb^*/^{238}U$	Th-corrected ages (Ma)[d] $^{207}Pb^*/^{206}Pb^*$
a. 30-63	.1	1421	12.3	7290 ± 11	20.004	16.690	58.7	59.7 ± .2	98	58.8 ± .1	95 ± 4
b. 63-80A	.1	665	6.0	4320 ± 6	19.652	15.589	60.9	61.2 ± .2	74	61.0 ± .1	71 ± 4
c. 80-100A	.2	511	4.7	6444 ± 8	19.028	16.906	62.8	66.7 ± .2	208	62.9 ± .1	205 ± 3
d. 100-350A	.1	758	6.6	7436 ± 11	20.299	19.621	59.5	59.6 ± .2	64	59.6 ± .1	60 ± 4
e. 100-350A	.1	517	5.0	5594 ± 8	18.612	16.448	64.8	69.9 ± .2	246	64.9 ± .1	243 ± 3

Note. Pb^* is radiogenic Pb.

[a] The letters "a," "b," etc. designate conventional multigrain fractions; "A" designates fractions abraded to 30%–60% of original mass. Zircon fractions are nonmagnetic on Frantz magnetic separator at 1.8 amps, 15° forward slope, and side slope of 1°.

[b] Reported ratios corrected for fractionation (0.125% ± 0.038%/AMU) and spike Pb. Ratios used in age calculation were adjusted for 2 pg of blank Pb with isotopic composition of $^{206}Pb/^{204}Pb = 18.6$, $^{207}Pb/^{204}Pb = 15.5$, and $^{208}Pb/^{204}Pb = 38.4$, 2 pg of blank U, 0.25% ± 0.049%/AMU fractionation for UO_2, and initial common Pb with isotopic composition approximated from Stacey and Kramers (1975) with an assigned uncertainty of 0.1 to initial $^{207}Pb/^{204}Pb$ ratio.

[c] Uncertainties reported as 2σ. Error assignment for individual analyses follows Mattinson (1987) and is consistent with Ludwig (1991). An uncertainty of 0.2% is assigned to the $^{206}Pb/^{238}U$ ratio based on our estimated reproducibility unless this value is exceeded by analytical uncertainties. Calculated uncertainty in the $^{207}Pb/^{206}Pb$ ratio incorporates uncertainty due to measured $^{204}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios, initial $^{207}Pb/^{204}Pb$ ratio, and composition and amount of blank. Linear regression of discordant data utilized by Ludwig (1992). Decay constants used: $^{238}U = 1.5513 \times 10^{-10}$, $^{235}U = 9.8485 \times 10^{-10}$, $^{238}U/^{235}U = 137.88$.

[d] A 75% ± 25% efficiency in ^{230}Th exclusion during zircon crystallization is assumed, and $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ ratios have been adjusted accordingly. Age assignments presented are derived from the Th-corrected ratios.

filled with chlorite and tourmaline, suggesting they are synplutonic. The Buckstock pluton lies just north of several mapped splays of the Denali fault system (fig. 4*a*) and may have intruded along an unmapped splay. Regardless of whether it was intruded along a fault, it provides evidence for northeast-striking dextral shear at 59.5 Ma.

Field relations in the Chuilnuk Mountains (fig. 5) show that some dextral movement took place in Late Cretaceous time. In the aureole of the 68-Ma Chuilnuk pluton (Decker et al. 1995), hornfels metasedimentary rocks of the Kuskokwim Group are folded about closely spaced, upright, north-trending axes; the pluton truncated the folds, indicating that folding predated pluton emplacement. In nearby areas, the Kuskokwim Group has yielded bivalves as young as late Coniacian or early Santonian (Box and Elder 1992); hence, the folding postdates the 87–85-Ma deposition but predates pluton emplacement at 68 Ma. Folds of this orientation are consistent with dextral shear, and their occurrence within only 10 km of the Denali fault suggests a genetic relation. The amount of offset during this episode is unknown.

To summarize, the Denali fault in the area of figure 2 has a total dextral displacement of 134 km, during various episodes and on various strands, since mid-Cretaceous time (fig. 6). Specifically, (1) deflected glaciers in the Alaska Range show 5–7 km of dextral displacement since 5.6 Ma; (2) some movement is inferred for late Oligocene to possibly earliest Miocene time (~22–28 Ma) during subsidence of the White Mountain basin; (3) offset plutons in the Alaska Range show 38 km dextral displacement since 38 Ma; (4) some movement is inferred for Early to Middle Eocene time (~46–55 Ma) during subsidence of the McGrath basin; (5) one strand was crosscut by the Tonzona pluton at 57 Ma and has not moved since; (6) the 59.5-Ma Buckstock pluton was emplaced in a northeast-trending dextral shear regime near the northern edge of the Denali fault system; and (7) dextral motion is inferred in the Chuilnuk Mountains between about 85 and 68 Ma.

The 2000-km-long Denali fault shows different amounts of offset, but similar times of motion, on its eastern and western limbs. The total displacement on the Denali fault in the area of figure 2 is less than half of the displacement on the opposite limb of the orocline. This discrepancy might be explained by some combination of thrusting on faults in the Alaska Range and strike slip on minor or unrecognized faults throughout the region. However, evidence for the age of displacement is consistent on both limbs. Richter and Matson (1971) recognized Holocene and Quaternary offsets across the Denali fault in eastern Alaska, comparable to item 1 above. Ridgway et al. (1995) presented evidence that the Oligocene-Eocene Burwash Basin of the Yukon Territory (fig. 1) was deposited during an episode of dextral displacement, consistent with items 2 and 3 above. A Paleocene (~59 Ma) episode of dextral motion (comparable to items 4 and 5 above) has not been explicitly recognized east of the area of figure 2 but is permitted by evidence from the hinge area of the orocline. Volcanic rocks

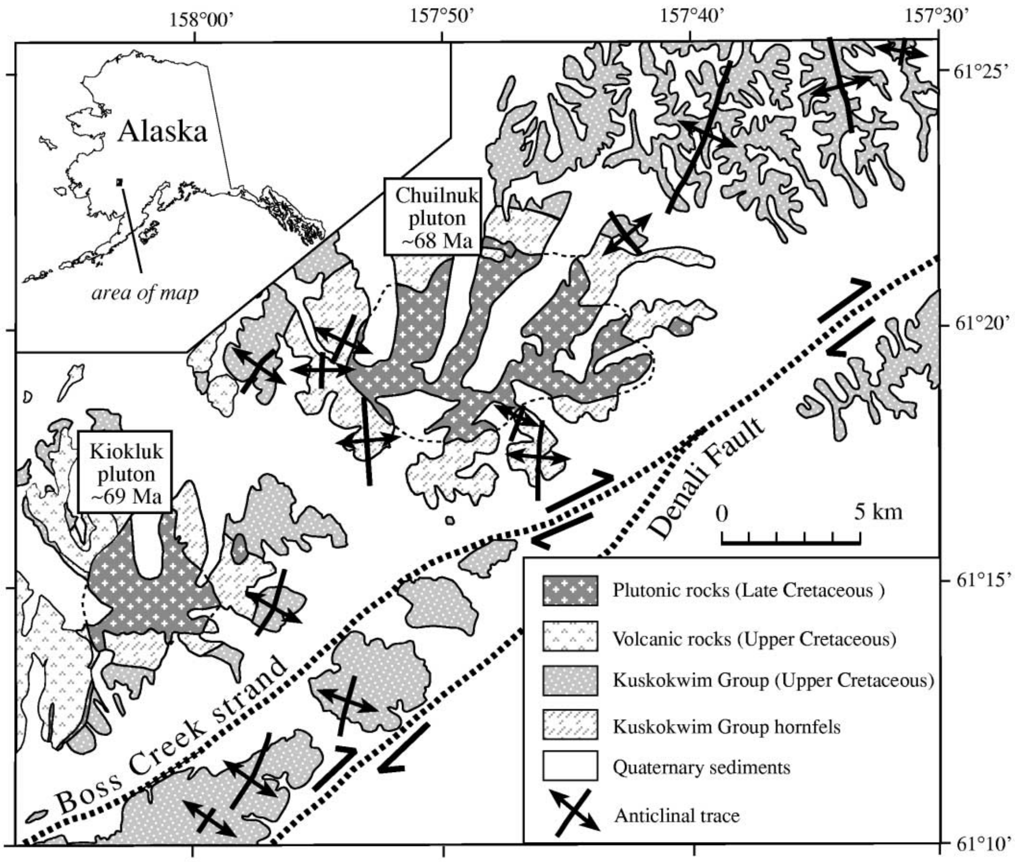

Figure 5. Geologic map of the Chuilnuk and Kiokluk Mountains area near the Denali fault. North-trending folds in the contact aureole of the Chuilnuk pluton suggest pre–68 Ma dextral motion on the nearby Denali fault system. Adapted from Decker et al. (1995).

in the Cantwell Basin (fig. 1) were erupted from 59.8 ± 0.2 to 55.5 ± 0.2 Ma (Cole et al. 1999), 10–20 m.yr. after a Late Cretaceous episode of north-south shortening (Ridgway et al. 1997). These volcanic rocks were deformed in a dextral shear regime sometime between the earliest Eocene and early Miocene (Cole et al. 1999). We speculate that Cantwell volcanism may itself have coincided with an episode of strike-slip displacement. Our 85–68-Ma episode of strike-slip motion in southwestern Alaska (item 6 above) has not been recognized as such on the eastern limb of the orocline.

Iditarod–Nixon Fork Fault. The Iditarod–Nixon Fork fault is one of the most significant strike-slip faults in Alaska (Grantz 1966; fig. 1). It can be traced from just west of the Sleetmute quadrangle to the Mount McKinley quadrangle, a distance of about 450 km (fig. 2). The northeastern part of the fault consists of several strands that cut the Farewell terrane (Patton et al. 1980; Dumoulin et al. 1999). The southwestern portion of the fault cuts the Kuskokwim Group, and in this sector there is a single, dominant strand. In the Iditarod quadrangle, a subparallel fault (Yankee-Ganes Creek) has a slightly older history and is also discussed in this section. The Iditarod–Nixon Fork fault cannot yet be traced with confidence very far beyond the limits of figure 2. Offset exceeds 88–94 km by an unknown amount. Specific evidence for fault movement will be discussed progressing from youngest to oldest.

Evidence bearing on the Neogene displacement history of the Iditarod–Nixon Fork fault system comes from two locations. In the central part of the fault system near Moore Creek (fig. 2), crosscutting relationships and modern placer deposit geomorphology suggest that gold-bearing drainages have been successively offset right laterally from their lode source (fig. 7). Two ancestral drainages of the gold-bearing Moore Creek monzonite are subparallel to, and lie southwest of, the modern drainage.

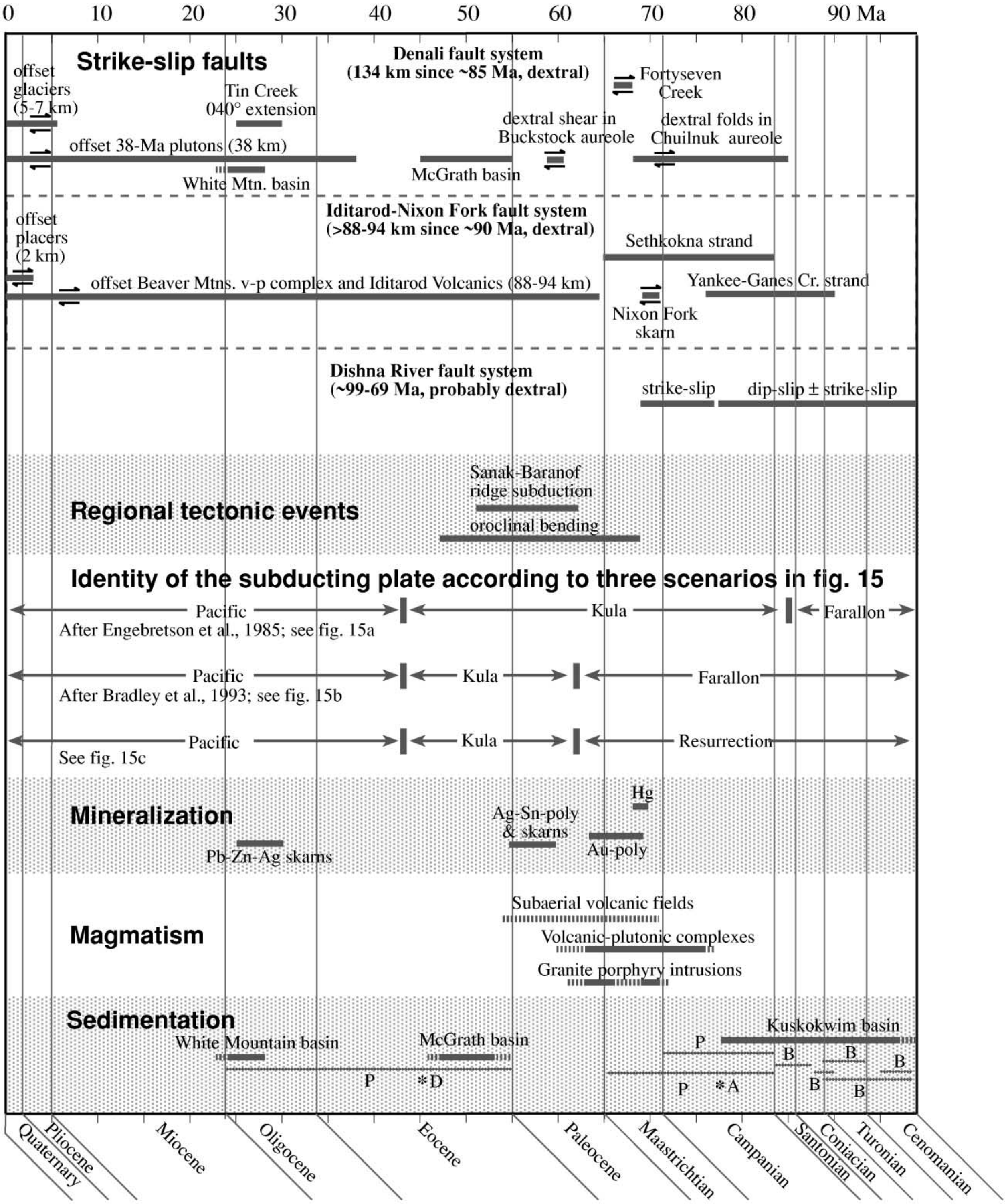

Figure 6. Time lines comparing ages of strike-slip motion, sedimentation, mineralization, and magmatism. Numerical calibration of the time scale is from Berggren et al. (1995) and Gradstein et al. (1994). Abbreviations are as follows for stratigraphic age controls: *P*, palynological age range; *B*, bivalve age range; **A*, isotopically dated ash layer; **D*, isotopically dated crosscutting dike.

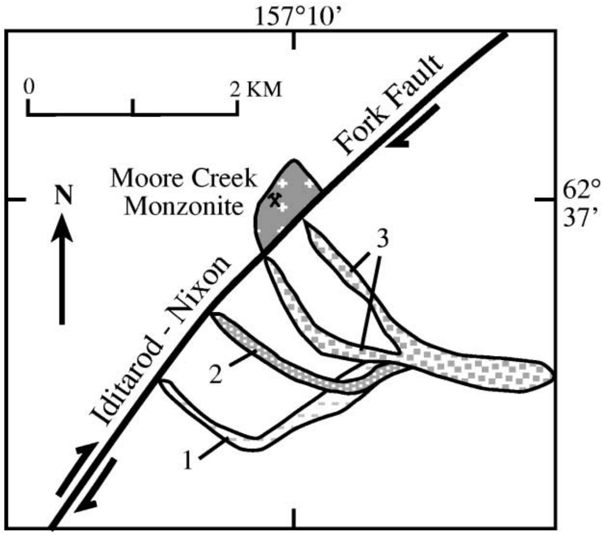

Figure 7. In the Moore Creek area of the Iditarod–Nixon Fork fault, crosscutting relationships indicate that streams draining the 70-Ma Moore Creek monzonite are successively older to the southwest (drainage 1 is the oldest; drainage 3 is modern). Drainage 1, which is thought to be of late Tertiary age, now lies 2 km southwest from the lode source, suggesting gold placer deposits have been right-laterally displaced from their lode source 2 km since late Tertiary time. Adapted from Bundtzen et al. (1988). Location shown in figure 2.

The relative age of the ancestral drainages (successively older to the southwest) is determined by their height above the modern floodplain and their crosscutting relationships (the youngest cuts both of the older drainages and the medium-aged drainage cuts the oldest). The oldest drainage lies 6 m above the modern floodplain and, although undated, is most likely late Tertiary in age based on correlation with similar deposits in interior Alaska (see, e.g., Hamilton 1994); the next younger drainage lies only 3 m above the modern floodplain and is thought to be early to mid-Pleistocene in age (Bundtzen et al. 1988). The oldest recognized gold placers lie approximately 2 km southwest of the lode source, suggesting that this much right-lateral displacement has occurred since late Tertiary time on this part of the fault system. Along strike to southwest in the Russian Mountains (about 20 km west of the area of fig. 2), a strand of the Iditarod fault system known as the Owhat fault is overlain by 6-Ma volcanic rocks that are not offset (Bundtzen and Laird 1991). Any movement since 6 Ma in this area must therefore have been taken up on another strand.

Convincing evidence for the sense and amount of displacement along the Iditarod–Nixon Fork fault has been found in the Iditarod quadrangle, where the fault cuts a Late Cretaceous and early Tertiary volcanic-plutonic complex and separates the two halves by 88–94 km in a dextral sense (Miller and Bundtzen 1988). On the northwest side of the fault, the Beaver Mountains volcanic field comprises an approximately 500-m-thick section divided into a dominantly andesitic basal tuff overlain by basalt and andesite flows. Because of extensive alteration of the basal tuff, age control is only available for the upper flow unit, and this ranges from 76 to 58 Ma (Miller and Bundtzen 1988). The volcanic section was intruded by comagmatic monzonitic plutons and is truncated on the southeast side by the Iditarod–Nixon Fork fault (Bundtzen and Laird 1982; Bundtzen et al. 1988). Approximately 90 km to the southwest, on the other side of the fault, are the Iditarod Volcanics (Miller and Bundtzen 1988), a 600-m-thick section comprised of basal tuff overlain by basalt and andesite flows. This section is lithologically identical to the volcanic rocks of the Beaver Mountains volcanic-plutonic complex, although no plutons are spatially associated with the Iditarod Volcanics at the current level of exposure. The volcanic section is truncated to the northwest along the fault (Miller and Bundtzen 1994). Limited K/Ar age control for the Iditarod Volcanics indicates the field ranges from as old as 77 Ma to as young as 63 Ma, very similar to the rocks from which they are apparently separated. Restoring the right-lateral displacement reunites the Iditarod Volcanics with the comagmatic stocks from which it was separated and also suggests that gold deposits at Donlin Creek and Independence (fig. 3) once formed a single mineralized trend (Miller et al., in press). As will be discussed in "Folding of the Kuskokwim Basin Fill," north-northeast-striking folds in the Kuskokwim Group along this section of the fault are also suggestive of dextral motion.

In northeastern Medfra quadrangle, a strand of the Iditarod–Nixon Fork fault, herein called the Sethkokna River fault zone (fig. 8), may also have been active during Late Cretaceous time. Along this strand is a narrow, topographically low belt of plant-bearing, nonmarine sandstone and conglomerate, which have yielded Late Cretaceous spores (Campanian-Maastrichtian; Patton et al. 1980). Massive debris-flow conglomerates in this sequence are interpreted as evidence for nearby high relief, likely associated with a Late Cretaceous phase of fault movement. These Cretaceous rocks are flanked on the east and west by a deep-water assemblage of chert, argillite, turbiditic sandstone,

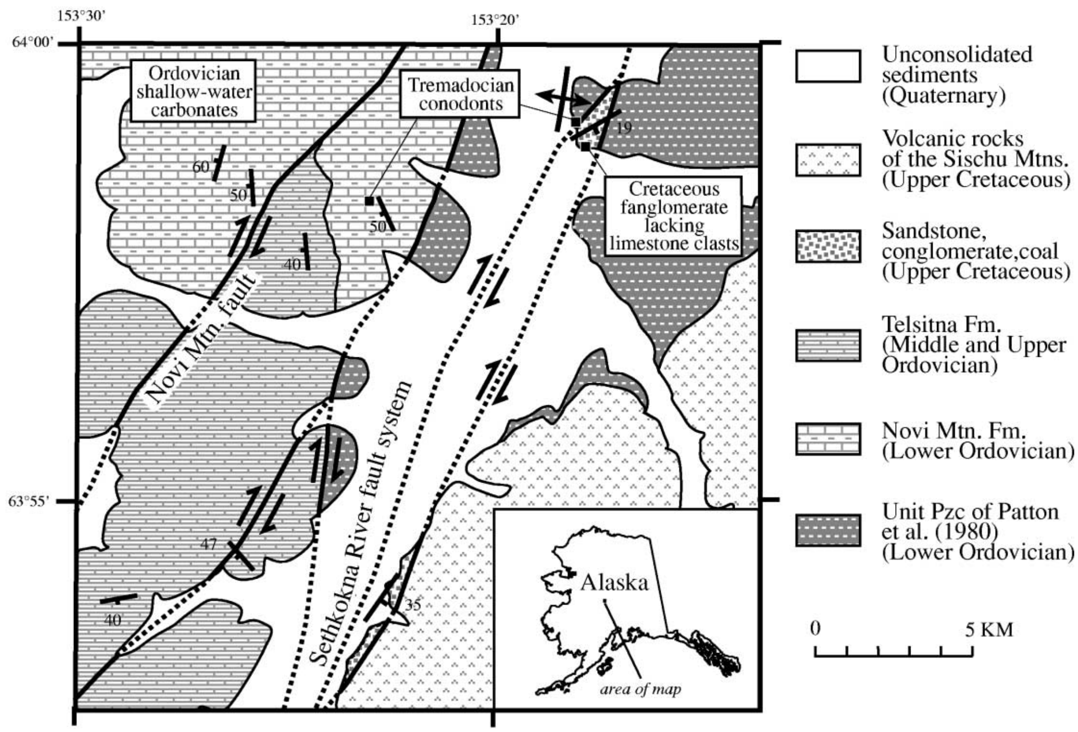

Figure 8. Geologic map of the Sethkokna River fault zone, part of the Iditarod–Nixon Fork fault system. Cretaceous conglomerates in a down-dropped block are devoid of carbonate clasts that might be expected had the highlands, now to the west, existed at the time. On either side of the fault, Ordovician strata of identical age are of contrasting shallow- and deep-water facies, suggesting significant offset. Adapted from Patton et al. (1980) and unpublished mapping by D. Bradley and J. Dumoulin.

and minor carbonate that has yielded Ordovician conodonts (Dumoulin et al. 1999; unit Pzc in fig. 8). Farther west is an extensive tract of Ordovician shallow-marine carbonate rocks (Novi Mountain and Telsitna Formations). Clasts in the Cretaceous conglomerates are largely chert and unmetamorphosed volcanic rocks; carbonate rocks are absent. Based on these observations, we can deduce that either the area west of the Sethkokna River fault zone was topographically low during Late Cretaceous time or the conglomerates have been displaced from their source. Facies studies of Ordovician units on either side of the fault strongly suggest the latter. Conodont assemblages of identical Early Ordovician age have been recovered from the shallow-water Novi Mountain Formation to the west of the fault, and from the deep-water rocks east of the fault. The two localities are only 8 km apart today but represent such different sediment types and depositional environments that they must have originated at least many tens of kilometers apart (Dumoulin et al. 1999). Assuming that the conglomerates were deposited during fault motion, the age of faulting would be Campanian to Maastrichtian (83.5–65 Ma), approximately coeval with movement along the Yankee-Ganes Creek strand, as described below.

The ~70-km-long Yankee-Ganes Creek fault is a subparallel strand of the Iditarod–Nixon Fork fault system (figs. 2, 9). The fault trace is marked by a string of at least six slivers of Innoko terrane chert surrounded by Kuskokwim Group sedimentary rocks, the latter showing no appreciable stratigraphic throw across the fault (figs. 9, 10; Bundtzen and Laird 1982, 1983). The distinctive map pattern—basement rock brought up along a straight fault zone—is most readily interpreted as positive flower structure (see, e.g., Harding 1985). The fault is buried by the Beaver Mountains volcanic-plutonic complex, the map boundaries of which show no significant offset. The oldest dated volcanic rocks from the Beaver Mountains sequence are 76 Ma (Miller and Bundtzen 1988); the volcanic rocks interfinger with shale and sandstone of the uppermost Kuskokwim Group. The map pattern and stratigraphic relations thus suggest that the

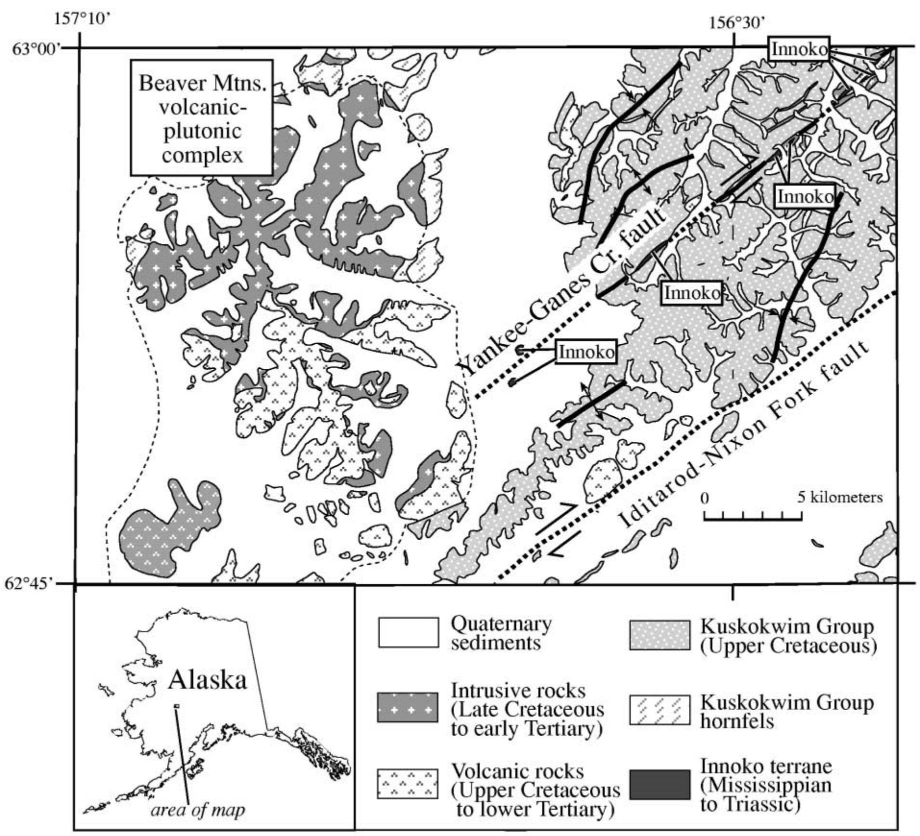

Figure 9. Geologic map of the Yankee-Ganes Creek fault zone, a strand of the Iditarod–Nixon Fork fault system. The fault zone is overlapped by the Beaver Mountains volcanic-plutonic complex, which shows no obvious offset along the Yankee-Ganes Creek trend. Adapted from Bundtzen and Laird (1982).

fault was active while part of the Kuskokwim Group was still being deposited but ceased by the time the volcanic rocks were erupted (Miller and Bundtzen 1992; fig. 10). Accordingly, movement on this splay is bracketed between the age of the oldest Kuskokwim Group (the only age-diagnostic fossils in this area are Turonian, 93.5–89 Ma; Miller and Bundtzen 1994) and eruption of the oldest volcanic rocks at 76 Ma.

To summarize, the Iditarod–Nixon Fork fault system in the area of figure 2 has a minimum dextral displacement of around 90 km and possibly much more. Specifically, (1) late Tertiary and Quaternary gold placer deposits have been offset ~2 km from their bedrock source, (2) matching halves of a volcanic-plutonic complex show a dextral offset of 88–94 km since 58 Ma, (3) the Sethkokna strand was active between 83.5 and 65 Ma, and (4) the Yankee-Ganes Creek strand was active between about 90 and 76 Ma. The amount of displacement during events 3 and 4 is unknown but would increase the total beyond 88–94 km by up to perhaps a few tens of kilometers.

Dishna River Fault. The Dishna River fault (figs. 2, 11) has only recently been recognized, perhaps because it lacks the pronounced topographic expression of the Denali and Iditarod–Nixon Fork fault systems. The presence of a fault along the northwestern margin of the Kuskokwim basin is inferred from the map pattern of elongate slivers of various basement terranes and Kuskokwim Group (fig. 11). We suggest that the fault was active during deposition of the Kuskokwim Group from Cenomanian to mid-Campanian (99–77 Ma) because, adjacent to the fault, the Kuskokwim Group is a basin-margin facies of fluvial sandstone, in contrast to deep-water turbidites that typify the Kuskokwim Group elsewhere (Miller and Bundtzen 1992). The presence of at least 7.5 km of Kuskokwim Group on the southeastern side of the fault indicates a significant dip-slip component during the time of basin subsidence; a strike-slip component during

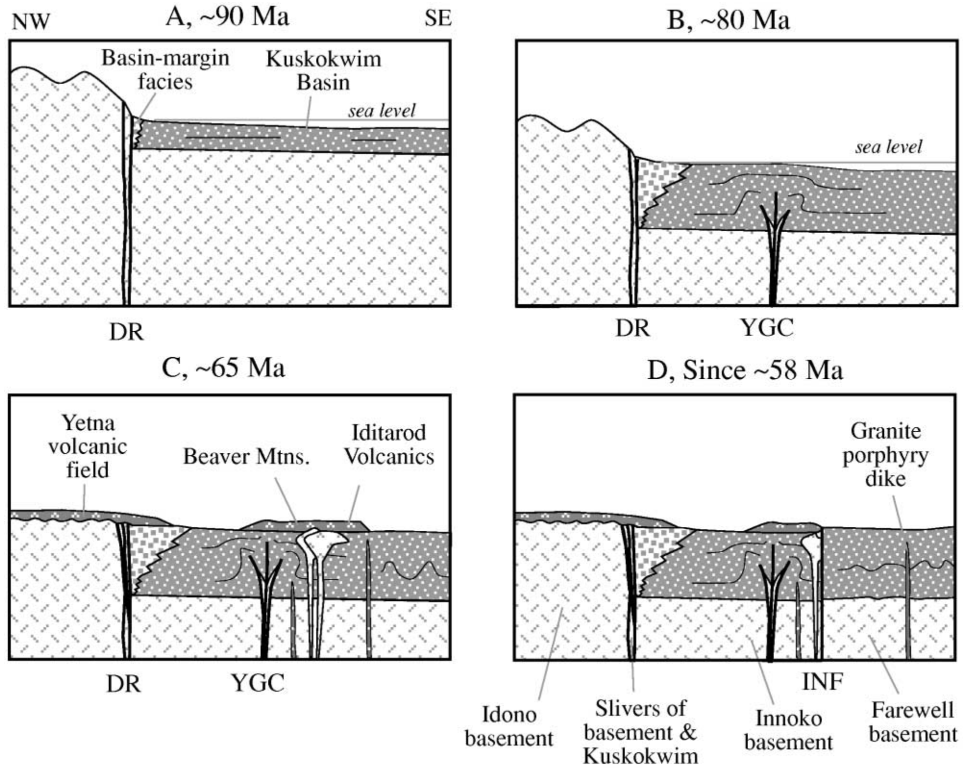

Figure 10. Cartoon cross section showing history of faulting in the Kuskokwim basin, Iditarod quadrangle. *A*, Around 90 Ma: Kuskokwim basin forms; dip slip and probable strike slip on Dishna River fault (*DR*). *B*, Around 80 Ma: Kuskokwim basin subsidence continues; flower structure develops along Yankee-Gaines Creek fault (*YGC*); fault-related folding of Kuskokwim Group. *C*, Around 65 Ma: Kuskokwim basin subsidence ends; Yankee-Gaines Creek fault buried by Beaver Mountains volcano-plutonic complex; Dishna River fault buried by Yetna volcanic field. *D*, Since ~58 Ma: ~88–93 km dextral strike-slip on Iditarod–Nixon Fork fault (*INF*).

this time is likely but cannot be demonstrated. Renewed or continued motion along the Dishna River fault zone juxtaposed slivers of Innoko terrane, Idono Complex, Ruby terrane, and Dishna River mafic-ultramafic rocks against each other and against basin-margin facies of the Kuskokwim Group. The pattern of anastomosing faults could conceivably have been produced by multiple dip-slip events of different polarity, but strike-slip faulting offers a far simpler explanation. No evidence is known for the sense of motion during this younger episode of movement, but its age is bracketed between 77 Ma (tuffs in basin-margin facies of the Kuskokwim Group) and 68.7 Ma, which is the oldest age determined from the Yetna volcanic field that overlaps the fault trace (Miller and Bundtzen 1994; fig. 11).

Southwest of the area of figure 2, the Sawpit fault (fig. 1) occupies a comparable basin-margin position. The history of motion that we recognize for the Dishna River fault in the Iditarod quadrangle is similar to that which Box (1992) interpreted for the Sawpit fault. Box inferred an early phase of basin-margin strike-slip faulting between late Cenomanian and Turonian time (96–89 Ma) on the basis of a progressive change of the western sediment source of the Kuskokwim Group. The Kuskokwim Group was deformed during subsequent right-lateral transpressive faulting, which appears to predate the eruption of the undeformed Swift Creek volcanic field (Box et al. 1993) at 74 Ma.

Summary of Strike-Slip History in Southwestern Alaska

The Denali, Iditarod–Nixon Fork, and Dishna River strike-slip fault systems of southwestern Alaska each have a complex history of motion. Dextral displacement across the Denali fault system totals 134 km and can be resolved into four intervals: (1) 5–7 km since the rise of the Alaska Range at 5.6 Ma, (2) 31–33 km between 5.6 Ma and the em-

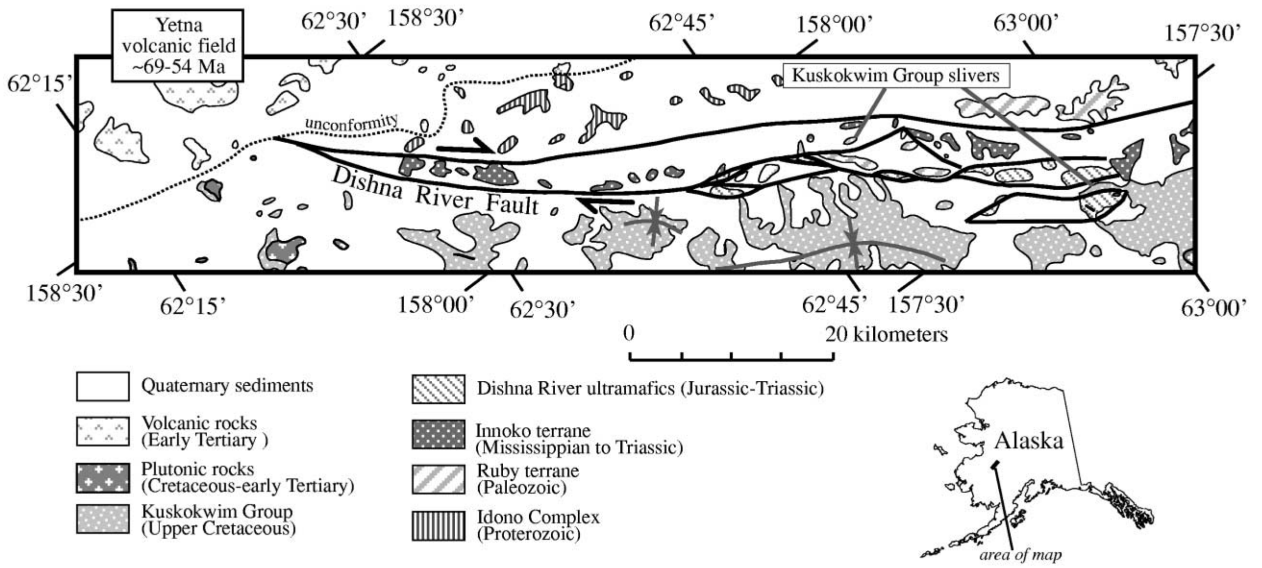

Figure 11. Geologic map of the Dishna River fault zone in the Iditarod 1 : 250,000 quadrangle. Fault zone consists of anastomosing faults that juxtapose slivers of various basement rock units and basin-margin deposits of Kuskokwim Group. The fault trace is overlain by the Yetna volcanic field. Adapted from Miller and Bundtzen (1994).

placement of the McGonagall and Foraker plutons at 38 Ma, (3) part of the remaining 96 km between 38 Ma and emplacement of the Chuilnuk pluton at 68 Ma, and (4) the rest between about 68 and 85 Ma. The Iditarod–Nixon Fork fault, which lies 115 km inboard of the Denali fault system, has a minimum 88–94 km dextral offset that can be resolved into three intervals: (1) 2 km since the late Tertiary, (2) 86–92 km between late Tertiary and the end of igneous activity at 58 Ma in the Beaver Mountains volcanic-plutonic complex, and (3) an unknown additional amount of displacement (probably not exceeding a few tens of km) between 77 and 85 Ma. The Dishna River fault, which lies 30–40 km inboard of the Iditarod–Nixon Fork fault system and is the northwestern bounding fault of the Cretaceous Kuskokwim basin, was active during the interval between Cenomanian and mid-Maastrichtian time (approximately 68–99 Ma) but has been inactive since then. The Denali and Iditarod–Nixon Fork fault systems were responsible for significantly offsetting the margins of the Kuskokwim basin and, locally, for deformation of the basin fill.

Folding of the Kuskokwim Basin Fill

Folds affecting the Kuskokwim Group show a complex map pattern. Five domains, numbered in order from north to south, can be recognized on the basis of the orientation of fold axial traces (fig. 12). These include (1) E-trending folds in the northeastern corner of the Kuskokwim basin, (2) NE-trending folds between the Dishna River and Iditarod–Nixon Fork faults, (3) en echelon NNE-trending folds on either side of the Iditarod–Nixon Fork fault, offset as 3a and 3b, (4) approximately E-trending folds between the Iditarod–Nixon Fork and Denali faults, and (5) N-trending folds near and between splays of the Denali fault. The main folding in all five domains appears to predate the volcanic-plutonic complexes, which typically have only gentle dips, compared to moderate to steep (and locally overturned) dips of most of the Kuskokwim Group.

The orientations of folds in domains 3a, 3b, and 5 and their proximity to the major strike-slip faults together suggest that they formed during episodes of dextral displacement. Along the Denali fault, folds in domain 5 are truncated by the 68-Ma Chuilnuk pluton, and they affect Kuskokwim Group strata that nearby have yielded bivalves as young as late Coniacian or early Santonian (ca. 87–85 Ma; Box and Elder 1992). Restoration of 88–94 km of dextral offset along the Iditarod–Nixon Fork fault implies that domains 3a and 3b formed together. The age of folding in domain 3 is not as tightly constrained; the folds affect strata that have yielded Turonian (93.5–89 Ma) bivalves (Miller and Bundtzen 1994) and are spatially associated with the Iditarod–Nixon Fork fault, on which the main phase of movement took place after 58 Ma. Al-

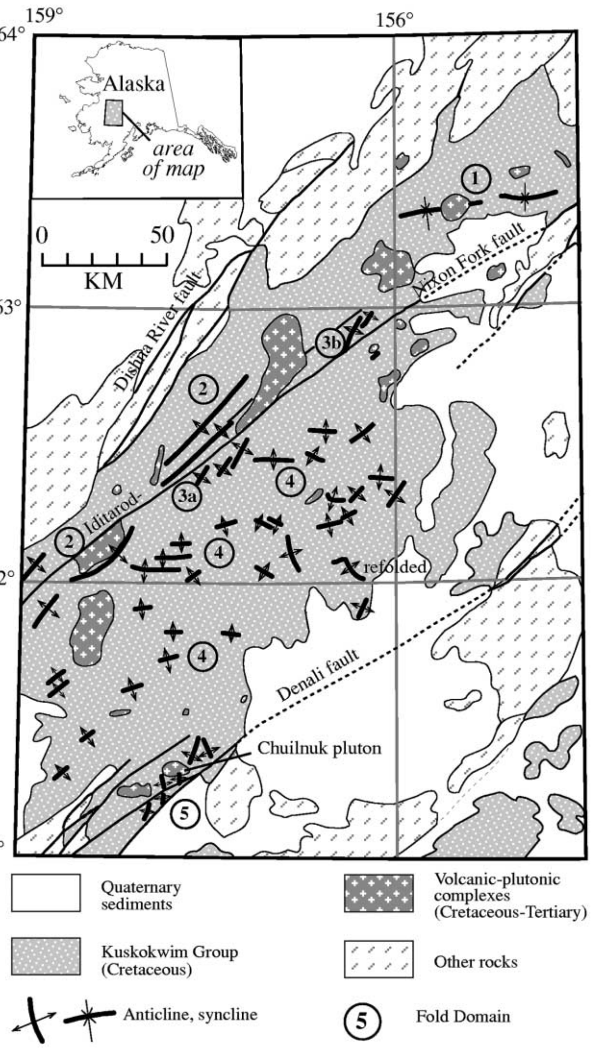

Figure 12. Map of a part of southwestern Alaska showing representative folds and numbered fold domains (see text) in the Kuskokwim Group. Adapted from Cady et al. (1955), Patton et al. (1980), Miller and Bundtzen (1994), and unpublished U.S. Geological Survey mapping.

though the folds of domains 3 and 5 have similar trends, there is no particular reason to think they are precisely the same age.

There is no obvious relationship between folds of the other three domains and a strike-slip regime. Folds of domain 1 deform rocks as young as late Turonian to early Coniacian (~91–87 Ma; fossil ages from Box and Elder 1992). Folds belonging to domain 2 trend roughly parallel to the northwestern basin margin and affect strata as young as a 77-Ma tuff interbedded with the basin-margin deposits (Miller and Bundtzen 1994). Roughly E-trending folds that comprise domain 4 occupy the broad area between the Denali and Iditarod–Nixon Fork faults. The youngest fossils so far recovered from this domain are Campanian to Maastrichtian (83.5–65 Ma) spores from black shale and graywacke intercalated with thin tuff bands (H. Hada, written comm., 1998). Folds of domains 1 and 4 indicate approximately north-south shortening and taken by themselves are not easily reconciled with a dextral strike-slip regime. However, as discussed below, simultaneous dextral faulting and north-south shortening might be explained in terms of regional strain partitioning related to oblique subduction. In the northeastern Sleetmute and southeastern Iditarod quadrangles, folds of domain 4 appear to have been refolded around approximately N-trending axes (fig. 12). The latter are parallel to folds of domains 3 or 5, but it is not known whether any of the roughly north-trending folds are coeval.

Mineral Deposits and Their Structural Setting

The time line (fig. 6) shows correlations between strike-slip faulting, regional tectonic events, igneous activity, sedimentation, folding, and ore-forming events. The structural observations discussed so far have been obtained through reconnaissance geologic mapping. One source of detailed structural data is studies of mineral deposits of Late Cretaceous and Tertiary age. Precious metal-enriched and polymetallic deposits of approximately 70 Ma are scattered throughout the Kuskokwim region (fig. 3; Bundtzen and Miller 1997). A few younger deposits (about 30 and about 60 Ma) are found along or very near the Denali fault system and, therefore, are potentially relevant to the displacement history. For the ~70 Ma age group, deposition of ore minerals was controlled by faults, typically of small scale (see, e.g., Sainsbury and MacKevett 1965; Bundtzen and Miller 1997). The sense of motion is known in only a few instances, in part because previous studies focused on ore controls rather than fault kinematics. Below we discuss key structural observations from the three age groups.

Within the area of figure 3, a few ~30 and ~60 Ma deposits are located in the Alaska Range near the Denali fault. A link between mineralization and movement along the Denali fault system is suggested at the Tin Creek–Midway lead-zinc-silver deposit (fig. 13). Skarn mineralization is related to emplacement of a swarm of granodiorite and diorite dikes that cut Paleozoic rocks of the Farewell terrane (Bundtzen et al. 1997). The dikes, and hence skarn formation, range in age from 25 to 30 Ma (Solie et al. 1991). The average strike of

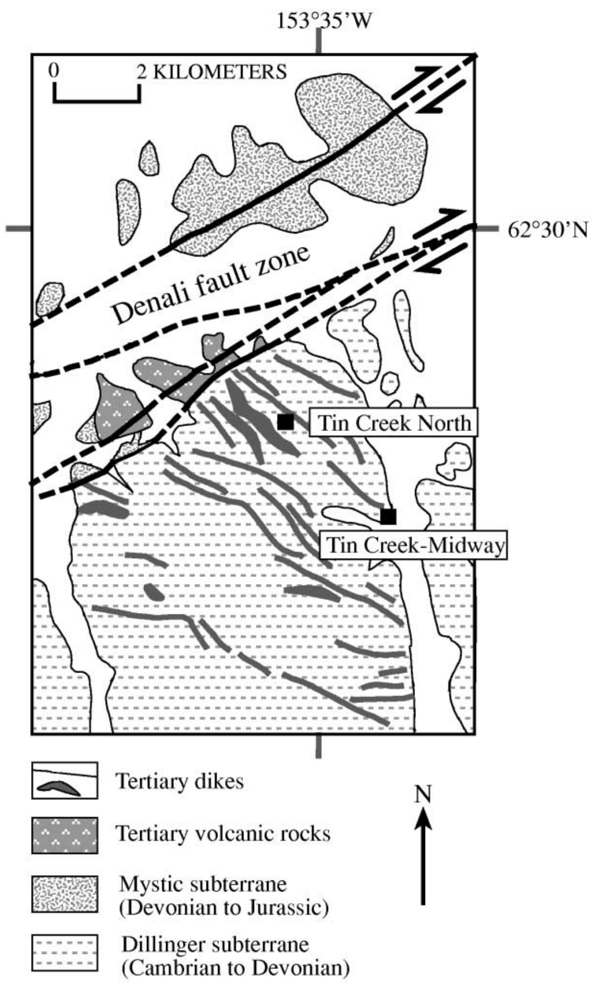

Figure 13. Map of Tin Creek area, adapted from Bundtzen et al. (1997). Approximately 25–30 Ma dike swarm associated with skarn mineralization suggests an extension direction consistent with a dextral shear sense along the Denali fault system, which bounds the dike swarm to the north.

dikes is about 310° (fig. 13), implying an extension direction that is consistent with dextral shear along the Denali fault just to the north. The few deposits of the ~60-Ma group are also pluton related and mostly tin-silver polymetallic types. The Purkeypile district (fig. 3) is associated with the Tonzona pluton, which, as discussed earlier, intruded across an unnamed northerly strand of the Denali fault system at 57 Ma. Ag-Cu-Pb-Sn ore deposition at Purkeypile (Millholland 1999) is nearly the same age as northeast-striking dextral shear deformation at the Buckstock pluton (fig. 4). Although detailed structural information is not available from Purkeypile, a temporal and spatial correlation with strike slip on the Denali fault system is likely.

The ~70-Ma deposits are the most widespread and economically significant in the region. They also furnish the most structural information and corroborate the episode of roughly north-south shortening that is suggested by the east-west folds of domains 1 and 4 (fig. 12). The two main deposit types of this age are intrusion-related gold-polymetallic systems (Bundtzen and Miller 1997) and epithermal mercury-antimony systems (Sainsbury and MacKevett 1965; Gray et al. 1997). Gold-bearing vein formation has been directly dated at two deposits, Fortyseven Creek at 67 Ma (Gray et al. 1998) and Donlin Creek at 69–70 Ma (Gray et al. 1997; Szumigala et al. 2000), and at many other deposits, associated ~70-Ma intrusions are assumed to be coeval with gold deposition (Miller and Bundtzen 1994; Bundtzen and Miller 1997; Bundtzen et al. 2000; Miller et al. 2000). Two mercury-antimony deposits (Fairview and Rhyolite) have isotopic ages of 73 and 71 Ma (Gray et al. 1997). Other undated mercury deposits probably formed at about the same time.

Kinematic data are available for two deposits that occur in the region between the Denali and Iditarod–Nixon Fork faults. At the Donlin Creek deposit (the largest gold deposit in the region), structures associated with the 69-Ma gold-forming event include a conjugate set of NW-striking dextral and NE-striking sinistral faults, NNE-striking dilatant veins, and E-striking thrust faults (Ebert et al. 2000; Miller et al. 2000). Together these indicate approximately north-south compression (Miller et al. 2000), which is roughly perpendicular to the principal compression direction that would be associated with dextral movement on the Denali and Iditarod–Nixon Fork faults. Kinematic data are also available from the ~70 Ma Red Devil deposit (the largest mercury mine in Alaska; fig. 3) that lies 30 km to the southeast. At Red Devil, mineralized dextral faults strike 310° (MacKevett and Berg 1963), implying a roughly north-south principal compression direction (fig. 14). Other gold and mercury deposits in the area (fig. 3) show structural trends that are similar to those just discussed. As at Donlin Creek, roughly NNE-striking veins and faults also host mineralization at Independence, Telephone Hill, and Goss Gulch (fig. 3). Roughly NW-striking faults host mineralization in the Horn Mountains and at Alice and Bessie (fig. 3).

Two deposits in the 70-Ma age group lie along the major faults and provide some indication of mineralization in a dextral wrench regime. At Fortyseven Creek (fig. 3), gold-bismuth-tungsten-bearing veins occur in a zone that parallels the Denali fault, which lies 4 km to the southeast. Con-

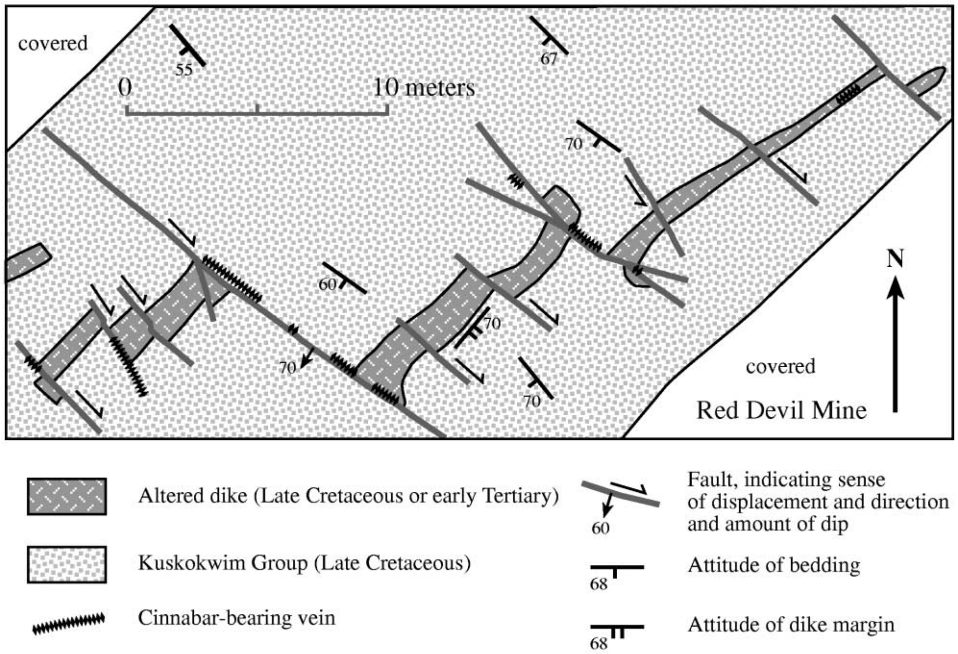

Figure 14. Sketch map from the Red Devil mercury mine, after MacKevett and Berg (1963)

jugate mineralized faults strike 310° and 075°; the latter set roughly parallels the Denali fault and locally causes dextral offsets (T. K. Bundtzen, unpub. data, 1999). At the Nixon Fork gold-skarn deposit, steeply plunging folds, sheet-like NE-striking intrusions, and occurrence of ore bodies in pressure shadows together suggest that the 70-Ma pluton responsible for mineralization was emplaced synkinematically during dextral strike slip along a strand of the Iditarod–Nixon Fork fault (W. McClelland, unpub. data, 1999).

The mineral deposits of the region thus provide fragmentary evidence that bears on the tectonic regime at around 30, 60, and 70 Ma. Structural observations from deposits of the ~30- and ~60-Ma groups are consistent with dextral strike slip on the Denali fault. Deposits of the ~70-Ma group send a mixed signal. Structures at Fortyseven Creek and Nixon Fork mine (fig. 3) are consistent with dextral strike slip on the Denali and Iditarod–Nixon Fork faults, respectively. Structures at Donlin Creek suggest roughly north-south compression. On the basis of the available evidence, the most straightforward explanation for this mixed signal is partitioning of deformation on a regional scale (e.g., Dewey 1980). In this interpretation, the region between the Denali and Iditarod–Nixon Fork faults was subject to regional north-south compression while strike slip was taking place along the main faults (Miller et al. 2000*a*, 2000*b*). An alternative explanation, but one that cannot be resolved with currently available geochronology, would involve a succession of rapid changes of the tectonic regime across the entire region.

Synthesis

We combine evidence from the Kuskokwim region with the regional plate-tectonic constraints to summarize the history of, and explore possible explanations for, the strike-slip faulting in southwestern Alaska. No single mechanism can explain all of the ~95 million-year history of dextral strike-slip faulting in southwestern Alaska. The account must consider complications inherent to the southern Alaska orocline; hence we discuss the history in terms of pre-, syn-, and postorocline. Prior to 40 Ma, reconstructions involve assumptions about the identity of the subducting plate, position of subducting ridges, amount of northward terrane transport, and timing of oroclinal bending. These factors cast doubt on published reconstructions and specifically relative plate motion vectors.

Displacements since Formation of the Orocline: Late Eocene to Present. Since Late Eocene time, southwestern and south-central Alaska have been relatively stable. The orocline had formed (Coe et al. 1989), coast-parallel terrane translations had largely been completed (Hillhouse and Coe 1994), and the identity and relative motions of the subducting plate—the Pacific—can be inferred with confidence (Atwater 1989). Because the plate-tectonic setting is not in question, this interval is particularly revealing.

Both the Denali and Iditarod–Nixon Fork faults have undergone Neogene dextral motion (fig. 6). Redfield and Fitzgerald (1993) showed Pacific–North America relative motions for various points along the Denali and Iditarod–Nixon Fork faults. For the interval between 5.6 Ma and the present, these vectors have a sinistral component of obliquity. Evidently, Neogene dextral motion across these faults has taken place in spite of the local direction of relative motion of the Pacific Plate with respect to North America (fig. 1). A driving mechanism other than oblique subduction must therefore be sought. Considering a broader region (fig. 1), the Pacific Plate is moving north-northwest relative to the North American Plate along most of the Cordilleran margin, producing dextral motion on margin-parallel strike-slip faults such as the eastern Denali and Queen Charlotte faults. Where these faults bend in Alaska, dextral motions could simply be caused by a push from the southeast, driving crustal blocks around the oroclinal bend (e.g., fig. 3 of Coe et al. 1989). A variant on this mechanism involves westward extrusion of crustal blocks from interior Alaska toward the Bering Sea (Scholl et al. 1992; fig. 1). This mechanism has been invoked for early Tertiary time (as discussed below) but may continue to operate today. In this broader context, the subduction direction of the Pacific Plate (and Yakutat block that is traveling with it and colliding with eastern Alaska; Plafker et al. 1994) has indeed been responsible for the Neogene strike-slip faulting in southwestern Alaska, but in a roundabout way. The present-day subduction direction beneath southwestern Alaska, when considered alone, does not predict the observed sense of strike slip.

Some of the strike-slip motion in southwestern Alaska took place earlier in the post orocline period. In the area of figure 2, about 31–33 km of dextral displacement is inferred for the Denali fault during Late Eocene through Miocene time. This offset is obtained by subtracting the 5–7 km of displacement since the rise of the Alaska Range (at the end of the Miocene) from the total 38 km of displacement that has accumulated since the emplacement of the Foraker and McGonagall plutons (in the Late Eocene). Timing of displacement on the Iditarod–Nixon Fork fault is not known in detail; all but 2 km of the observed 88–94 km of dextral map separation accumulated between 58 Ma and latest Tertiary time.

During Oroclinal Bending: Paleocene to Middle Eocene. Uncertainties begin to mount during early Tertiary time when (1) the southern Alaska orocline formed (Coe et al. 1989) and (2) a ridge was subducted beneath southern Alaska (Bradley et al. 1993). Both of these events hinder interpretation of the mechanisms that drove strike-slip faulting—the first because it alters the convergence vectors and the second because it calls into question the identity of the subducting plate. First, oroclinal bending is an important consideration because the Denali and Iditarod–Nixon Fork faults, on the western limb, would have been significantly reoriented with respect to the convergence direction of any subducting plates. Paleomagnetic data suggest that between 44 and 66 Ma, southwestern Alaska rotated about $44° \pm 11°$ counterclockwise with respect to cratonic North America (Coe et al. 1989). Even the maximum amount of rotation (55°) permitted by the paleomagnetic data does not completely account for the ~65° difference in strike of the Denali fault on either limb of the orocline. This implies that an original, gentler bend in the fault was merely magnified during early Tertiary time. Second, most Late Cretaceous to early Tertiary marine-based plate reconstructions show a Kula-Farallon spreading center that intersected the western margin of North America. The location of this trench-ridge-trench triple junction is unclear (fig. 15). Engebretson et al.'s (1985) northern option (fig. 15*A*) put the subducting ridge in Washington. Based on the presence of a 2200-km-long belt of near-trench plutons (Sanak-Baranof belt), Bradley et al.'s (1993) reconstruction put the subducting ridge in Alaska (fig. 15*B*). A viable alternative, however, is that there were two subducting spreading ridges, one in southern Alaska and one in Washington (or farther south), and that they were separated by a previously unrecognized plate (Resurrection Plate in fig. 15*C*; Haeussler et al. 2000; Miller et al. 2000*a*, 2000*b*; Bradley et al., in press). Relative motion vectors have been calculated and used in regional tectonics this far back in time (see, e.g., Wallace and Engebretson 1984; Plafker and Berg 1994), but until the identity of the subducting plate is resolved, this approach will lead to dubious conclusions.

Within the Kuskokwim region, our data show that both the Denali and Iditarod–Nixon Fork faults underwent dextral motion during the 44–66-Ma interval. Grantz (1966) proposed a regional-scale flexural slip mechanism associated with oroclinal bending to explain dextral strike-slip motions on

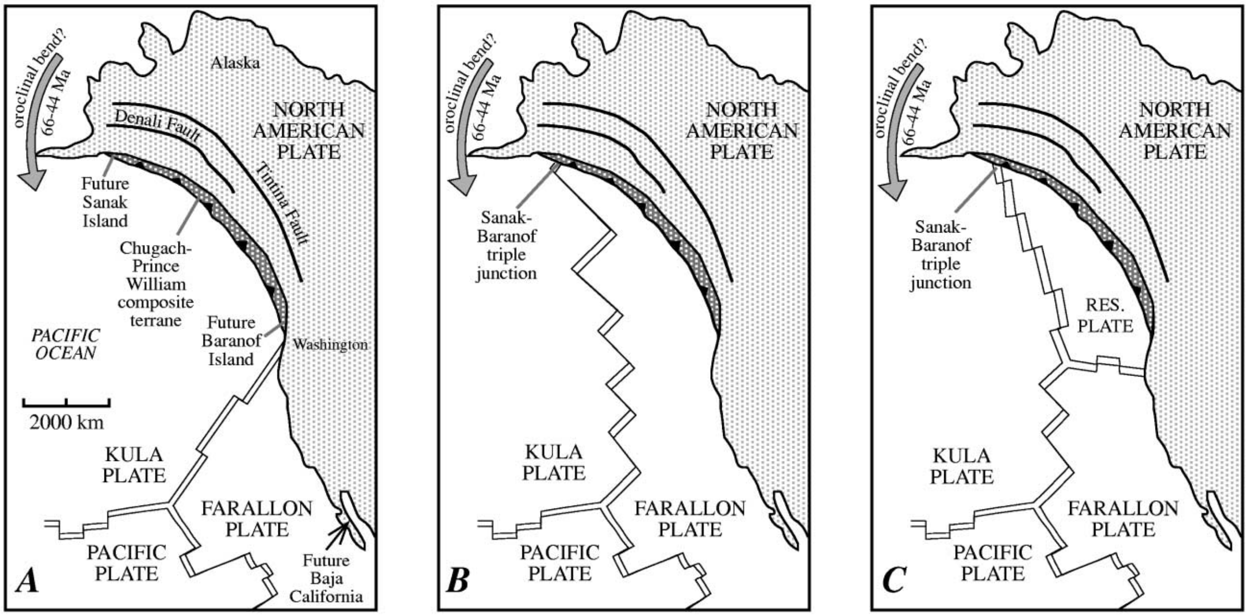

Figure 15. Alternative hypothetical plate reconstructions for ~60 Ma bearing on the identity and trajectory of plates subducted beneath interior Alaska. In all three, the Chugach–Prince William terrane has been restored to its original position approximately 820 km farther south, in keeping with the geologic constraints discussed in text. *A*, Engebretson et al.'s (1985) northern option for the position of the Kula–Farallon–North America triple junction. *B*, Kula-Farallon ridge being subducted beneath the Chugach–Prince William terrane, a modification of the Bradley et al. (1993) reconstruction. *C*, A third possibility is that the Sanak-Baranof triple junction was related to subduction of a ridge that separated the Kula Plate from the hypothetical Resurrection Plate (*RES.*) to the east.

preexisting faults in southwestern Alaska. Coe et al. (1989) referred to this process as "megakinking" and suggested that the amount of implied flexural slip was consistent with the paleomagnetic rotations. The timing of oroclinal bending and strike-slip motions is so poorly constrained that we cannot fully evaluate this model with geologic data. However, several observations suggest that, at best, megakinking can only be part of the story and only applies to a limited interval in a long history of strike slip. The megakinking model (as illustrated by Coe et al. [1989], their fig. 4) provides no explanation for dextral displacement on the eastern limb of the orocline or for the pre- or postorocline dextral strike-slip motions on the western limb. Scholl et al. (1992) also related strike-slip faulting to oroclinal bending, but by means of a continental escape mechanism. In this interpretation, crustal shortening in eastern Alaska was accompanied by westward extrusion of crustal blocks toward a free face in the Bering Sea (fig. 1). The strike-slip faults of southwestern Alaska facilitated this westward tectonic escape. It is not known how these faults relate to a roughly perpendicular system of Middle Eocene strike-slip faults along the Beringian margin (Worrall 1991; fig. 1). Scholl et al. (1992) suggested that escape took place between ~59 and 42 Ma. Evidence for strike-slip movements both before and after this interval suggests the possibility of escape tectonics at other times as well.

Late Cretaceous: Prior to Oroclinal Bending. We have evidence for dextral motion on the Denali fault and indications of strike-slip motion, presumably also dextral, on two strands of the Iditarod–Nixon Fork fault system during the 85–66-Ma interval. Given that the orocline is younger, this early episode of dextral motion is perhaps most readily interpreted as the consequence of oblique subduction as per Fitch (1972), Dewey (1980), and Jarrard (1986) of the Farallon Plate (fig. 15*B*) or Resurrection Plate (fig. 15*C*). This interval corresponds to a time of northward terrane translation in the Canadian Cordillera (Irving et al. 1996).

The evidence reviewed thus far suggests a dextral strike-slip regime has operated almost continuously between about 83 Ma and the present. However, some events at ~70 Ma cannot be readily explained in terms of dextral wrench tectonics. Much of the Kuskokwim basin was folded about roughly east-west axes (domains 1 and 4; fig. 12). As noted above, folding took place after at least the bulk of the Kuskokwim Group was deposited, and most folding predated emplacement of the volcanic-plutonic complexes. Folds of domains 1 and 4 appear unrelated to particular strike-slip faults but rather suggest regional shortening due to roughly north-south compression. As discussed in "Mineral Deposits and Their Structural Setting," structures associated with ~70-Ma gold mineralization at Donlin Creek imply north-south compression. Approximately north-south shortening during this narrow time range is not restricted to the Kuskokwim region. In the central Alaska Range, 250 km to the east, deposition of the Cantwell Formation took place in an environment of regional north-south shortening during late Campanian to early Maastrichtian time (Ridgway et al. 1997). Magmatism in this continental back-arc region also peaked at ~70 Ma. Nonetheless, evidence does exist for dextral strike slip along the Denali and Iditarod–Nixon Fork faults at ~70 Ma. As mentioned previously, partitioning (e.g., Dewey 1980; Dewey et al. 1998; Saint Blanquat et al. 1998) of deformation on a regional scale provides the best explanation for apparently simultaneous north-south compression and dextral strike-slip along the region's main faults.

Cenomanian to Campanian: Early History of Kuskokwim Basin. The early history of the Kuskokwim basin remains problematic. Combining the evidence discussed previously from the Dishna River and Sawpit faults, it would appear that the northwestern margin of the Kuskokwim basin was a dextral strike-slip fault during at least part of the time of basin subsidence from Cenomanian to mid-Campanian (approximately 97–77 Ma). Renewed or continued strike-slip faulting would then have been responsible for producing a flower-structure-like map pattern in which basin-margin deposits are now preserved between various fault strands (fig. 11).

Cumulative Dextral Displacement on the Western Limb of the Southern Alaska Orocline. Dextral offsets on the Denali and Iditarod–Nixon Fork faults in the area of figure 2 sum to 212–218 km. Additional unquantified strike-slip offsets took place during the Cretaceous on the Dishna River and Iditarod–Nixon Fork faults and, presumably, on various minor faults that we have not considered. Outside the area of figure 2, but still on the western limb of the orocline, the Kaltag fault (fig. 1) has a dextral offset of 160 km since about 112 Ma (Patton et al. 1984); the Castle Mountain fault has a dextral offset of perhaps 20 km since the end of the Paleocene (Fuchs 1980); and dextral displacement since the Eocene on the Border Ranges fault is controversial but probably did not exceed a few tens of kilometers in south-central Alaska (Little and Naeser 1989). Therefore, cumulative dextral displacement on the western limb of the orocline is at least 400 km and could be as great as 450 km. This is only half of the geologically constrained ~830 km displacement (and even less than the 1000–4000 km of paleomagnetically derived displacement). As mentioned before, this discrepancy might be explained by some combination of thrusting and unrecognized strike-slip faulting.

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